



## Influence of the Hydric State and Lime Treatment on the Thermal Conductivity of a Calcareous Tufa

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### Abstract

An experimental study was conducted to investigate changes of thermal conductivity of a raw and lime-treated calcareous tufa (north-west of Algeria) during drying process. Treated (with 4% of lime) and untreated samples were prepared by static compaction at the Standard Proctor Optimum (SPO), Modified Proctor Optimum (MPO) and at a constant stress level of 4 MPa. Transient Hot Wire (THW) method was used to measure the thermal conductivity and the water content and degree of saturation of samples were determined at various drying times. Results show that the drying process induces a decrease in thermal conductivity. This parameter seems to vary linearly with the water content and the degree of saturation. In addition, it was found that the lime treatment leads also to a decrease in the thermal conductivity. Thus, the drying process and the lime treatment will jointly contribute to the reduction of the thermal conductivity of the studied material in such a way that it is more insulating than some traditional building materials like concrete or fired bricks.

*Keywords:* Thermal Conductivity; Water Content; Degree of Saturation; Tufa; Lime Stabilization.

### 1. Introduction

Currently, the energy consumption during the life cycle of modern buildings is very important. For residence buildings, it is estimated between 150 and 400 kWh/m<sup>2</sup>/year. However, for office buildings, this consumption ranges from 250 to 550 kWh/m<sup>2</sup>/year [1]. In Algeria, the building sector represents more than 34% of the total national consumption energy [2]. In view of these high energy demands, it is required today to limit its consumption within the construction envelope through the use of environmentally-friendly materials. It has been shown that natural earth materials are well suited to fulfill the above-mentioned requirements. The most widespread earth construction techniques used around the world are adobe, cob, rammed earth and compressed earth bricks (CEB). Note that these earthen techniques could help to reduce the energy consumption during the construction and exploitation phases of buildings [3, 4]. Furthermore, they can as well help to appreciably limit the negative impact of conventional construction materials on the environment [5].

In terms of thermal behavior of earthen materials, several research works have suggested that their thermal efficiency can be influenced by a number of factors as: the mineralogical composition, density or porosity, water content, degree of saturation and type of stabilizer [6-8]. The role of the density on the thermal conductivity was well

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established in the literature. The majority of results are in accordance that increasing in density (decreasing porosity) induces also an increase in thermal conductivity. For example, [9] made an evaluation of the thermal conductivity on unfired clay bricks. They indicated that this parameter and the dry density are linearly correlated. Mansour et al. (2016) [10] studied the influence of compaction pressure on the bulk density, and consequently, on the thermal performance on compressed earth bricks (CEB). They found out that the thermal conductivity of CEB decreased linearly as their bulk density decreased. It is noted that the obtained values of the thermal conductivity were between 0.618 and 1.483  $W \cdot m^{-1} \cdot K^{-1}$ . For its part, Laurent (1987) [11] indicated the existence of an exponential relationship between dry density of eight earthen materials and thermal conductivity. A limited number of research studies have assessed the effect of water content or degree of saturation on the thermal conductivity of earthen materials. This is due probably to the complexity of soil's thermal behavior and to interactions of liquid and gas phases within the solid matrix. Generally, it was observed that the thermal conductivity increases when the water content increases [11-13]. However, the influence of the hydric state (water content or degree of saturation) have different tendencies in literature. In terms of water content, a linear tendency was observed especially for lower water content values. Nevertheless, when water content increases, tendencies display a non-linear behavior as remarked in the work of Meukam et al. (2004) and Phung (2018) [12, 14]. Regarding the stabilization, it was revealed that lime is a highly responsive binder that can help optimizing both the mechanical and thermal behaviors of the compacted earthen materials at the same time [15-17]. In the case of [17], they made a comparison between the measured hygrothermal performances and the microstructural composition of stabilized clay-based mixtures. They indicated that the reduction in the thermal conductivity was attributed to pouzzolanic effect of lime stabilization. Akinmusuru (1994) [18] performed an investigation on the effect of stabilization on the thermal conductivity of tropical soil bricks. The samples under study were stabilized with cement and lime contents equal to 3, 5, 7 and 9%. It was shown that the stabilization tends to decrease the thermal conductivity. Ashour et al. (2015) [7], carried out an analysis of the thermal conductivity of unfired clay bricks reinforced with straw fibers and also stabilized with cement and gypsum. They indicated that the dry density of bricks decreased when the fiber content increased, which induced a thermal conductivity ranges between 0.96 and 0.31  $W \cdot m^{-1} \cdot K^{-1}$  corresponding to fiber percentage contents varying between 0 and 3%. Meukam et al. (2004) [12] found out that incorporating cement decreases the thermal conductivity and density of compressed earth bricks.

The present work aims to study the thermal conductivity of a local material used in the formulation of compressed earth blocks (CEB). This material is a calcareous tufa available in abundance in different regions of Algeria and widely used in roads construction [19-21]. Raw and lime-treated compacted samples were considered in order to investigate the effect of the hydric state (water content and degree of saturation) variations on the thermal conductivity. Furthermore, the effect of the stabilization with lime during the drying process on the thermal conductivity was also examined. Thus, this paper will be organized in four sections: after an introduction, a complete identification of the material, samples preparation and experimental procedures will be presented in the materials and methods section. Afterwards, in the results and discussion section, the influence of the hydric state (variation of water content and degree of saturation) during drying process and lime stabilization, on thermal conductivity will be presented and discussed in the light of literature results. Finally, a conclusion will outline the principal results and findings of this work.

## 2. Materials and Methods

### 2.1. Materials Identification

The material used in this study originated from the region of Beni-Saf, located in northwestern Algeria. This area is well known for its calcareous soils (tufa). Only soil particles passing through a 5 mm sieve was used in the determination of the particle size distribution (Figure 1). The tufa utilized consisted of gravel (12%), sand (48%), silt (21%) and clay (19%). This material was characterized by a low plasticity index of 17% and a liquid limit equal to 37%. The main physical parameters of the studied soil are summarized in Table 1. According to the USCS classification, the tufa of Beni-Saf can be classified as clayey-sand (CS).

**Table 1. Physical parameters of Beni-Saf Tufa**

Parameters	Values	Standards
Gravel	12%	NF P 94-041[22]
Sand	48%	
Silt	21%	NF P 94-057[23]
Clay	19%	
Liquid limit	37%	NF P 94-051[24]
Plasticity index	17%	
Specific density	2,74	NF P 94-054[25]
Calcium carbonate content	85%	NF P 94-048[26]
Activity	0,9	

Figure 1 illustrates a comparison between the particle size curve of the tufa under study and the grading curve of the compressed earth brick (CEB) recommended by Standard XP P13-901 [27]. In addition, Figure 2 presents the positioning of the plasticity values with respect to the recommendation zone [27]. The two criteria, i.e. plasticity zone and grading curve, show that the tufa from Beni-Saf meets the requirements for the manufacture of compressed earth blocks.

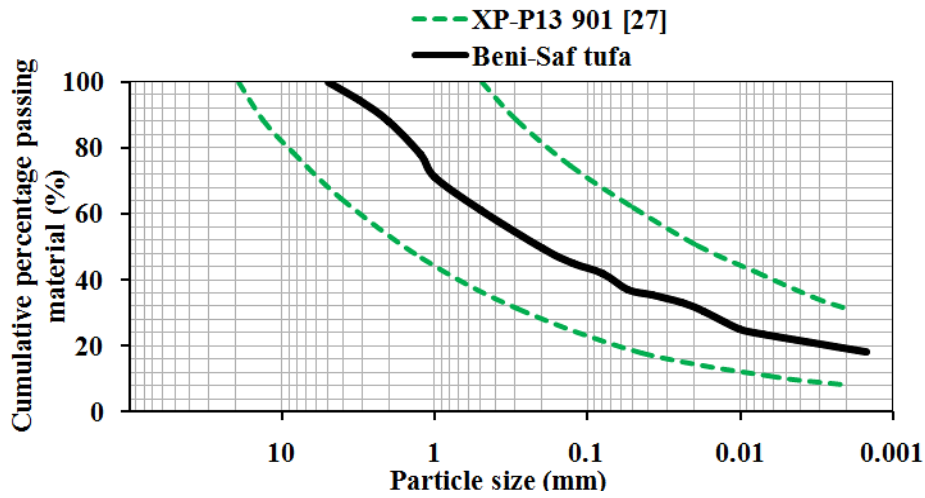


Figure 1. Particle size distribution of tufa from Beni-Saf

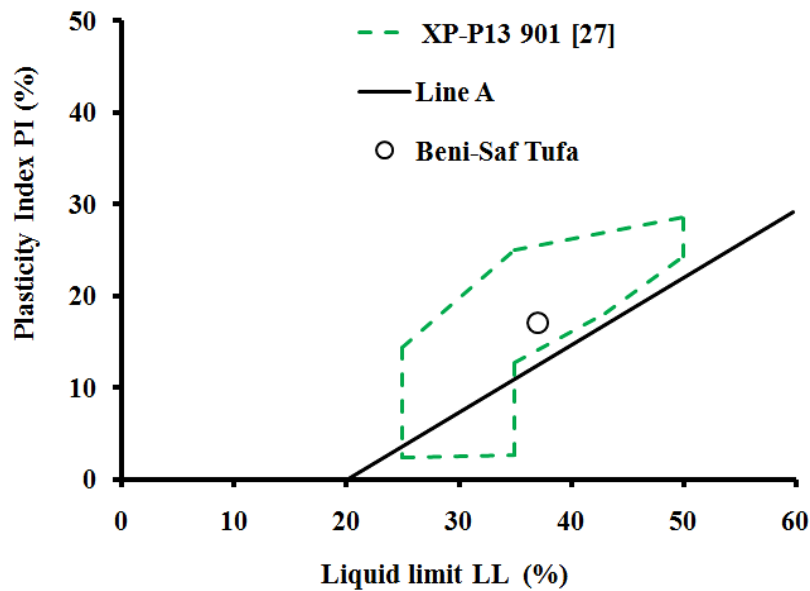


Figure 2. Recommended plasticity chart

Quicklime at 4% per dry weight of material was used in this study as a stabilization element. According to Sebâa et al. (2018) [28], this percentage gave an optimum compressive strength. The physico-chemical properties of lime used in this study are given in Table 2.

Table 2. Properties of lime used [29]

Physical properties	Chemical composition	
Bulk density 1490 kg/m <sup>3</sup>	CaO	> 82,77
Specific surface area 300 m <sup>2</sup> /kg	MgO	< 1,88
	Fe <sub>2</sub> O <sub>3</sub>	< 3,27
	Al <sub>2</sub> O <sub>3</sub>	< 10,63
	SiO <sub>2</sub>	< 1,35
	SO <sub>3</sub>	< 0,11
	Na <sub>2</sub> O	< 0,06
	K <sub>2</sub> O	< 0,15
	CaO	> 82,77

### 2.2. Sample Preparation

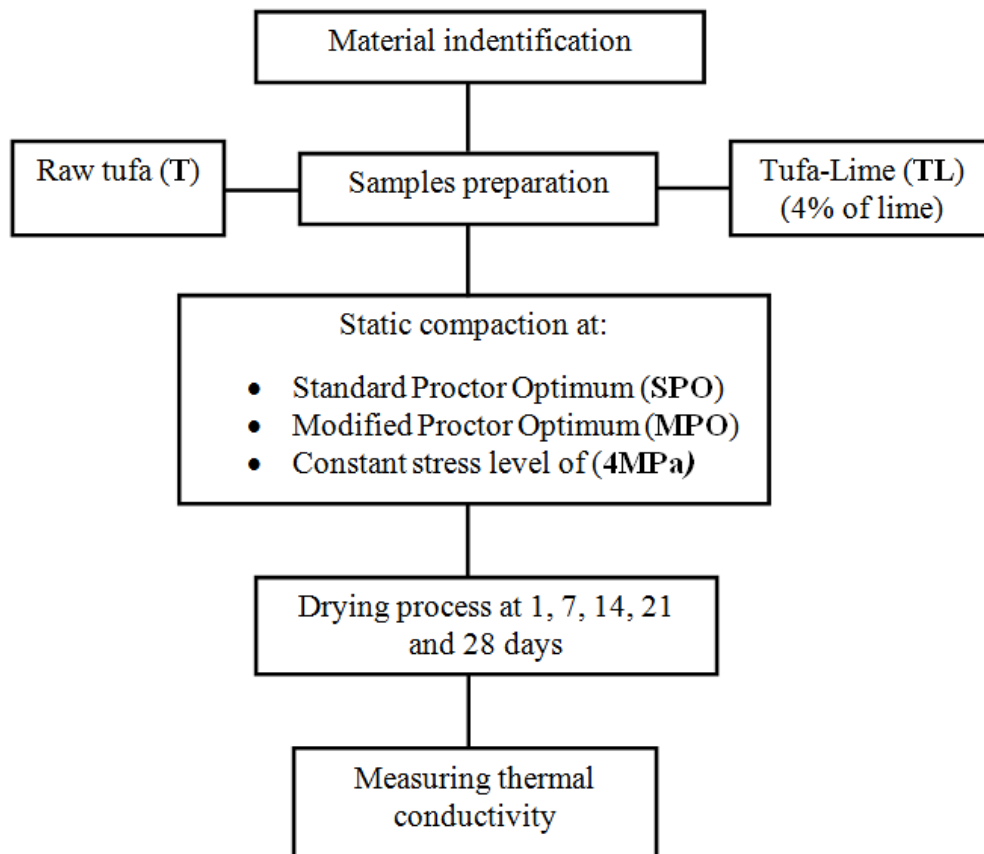
Table 3 presents the initial compaction conditions for different mixtures under study. They correspond to the maximum dry densities ( $\gamma_{dmax}$ ) and optimal water contents ( $w_{opt}$ ) obtained using the: (i) Dynamic compaction at Modified and Standard Proctor Optima (MPO, SPO) in accordance with Standard NF P94-093[30], (ii) Static compaction under the constant stress level of 4 MPa, at a rate of 1mm/min. Based on the obtained optima ( $\gamma_{dmax}$  and  $w_{opt}$ ), raw tufa (T-MPO, T-SPO, T-4 MPa) and tufa-lime mix (TL-MPO, TL-SPO, TL-4 MPa) samples were produced.

**Table 3. Initial compaction conditions of samples using the dynamic and static compactions.**

Materials	Energies	Sample's reference	Maximum dry density $\gamma_{dmax}$ (g/cm <sup>3</sup> )	Optimum water content $w_{opt}$ (%)	Degree of saturation Sr (%)
Tufa	MPO	T-MPO	1,98	12,7	90
	SPO	T-SPO	1,79	15	78
	4 MPa	T-4 MPa	1,83	13,5	75
Tufa + 4% Lime	MPO	TL-MPO	1,88	10,5	64
	SPO	TL-SPO	1,72	14	66
	4 MPa	TL-4 MPa	1,75	13,5	67

Once the soil was dried in the oven at 105 °C for 24 h, the appropriate quantities of soil were mixed with the corresponding amounts of lime in the dry state. After that, the desired water content (optimal water contents) was added to the different mixtures of soil and stabilizer. The mixture was then poured into double-piston cylindrical molds and compacted statically to the maximum dry density (Table 3). The final cylindrical samples were 50 mm in diameter with a height of 100 mm.

After compaction, the samples were demolded and dried for 1, 7, 14, 21 and 28 days at a temperature close to 20°C and a relative humidity greater than 50%. After the drying periods, the samples were weighed and their overall volume was established using a digital caliper in order to calculate their new densities. Additional series of undried samples were tested immediately after compaction. The following chart (Figure 3) summarizes the mains steps conducted in this study.



**Figure 3. Main steps of the study methodology**

### 2.3. Experimental Procedure

The general principle of measurement is based on the imposition of heat flow within the compacted samples via a probe. The device used to perform dynamic measurements implements the Transient Hot Wire (THW) method. A good contact must be ensured between the measuring surface of the probe and the sample (Figure 4.). The thermal response of the sample makes it possible to evaluate the thermal conductivity ( $\lambda$ ).

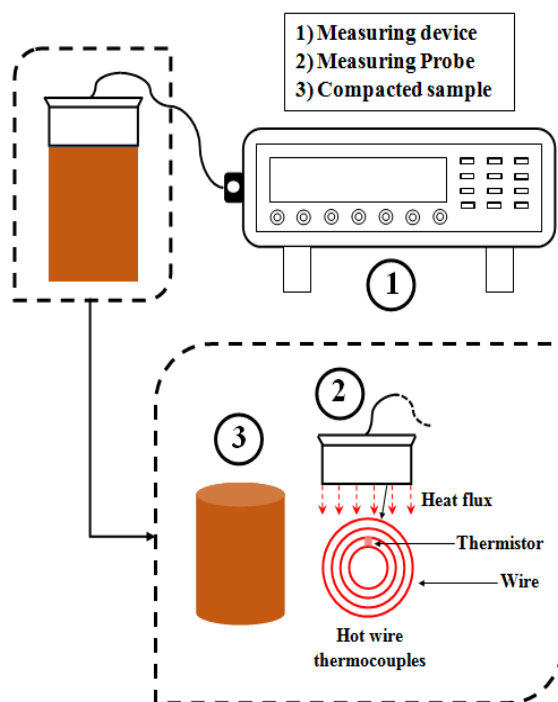


Figure 4. Experimental device used for thermal conductivity measurement

### 3. Results and Discussion

The variations of dry density as a function of drying periods of raw and stabilized tufa for different energies (SPO, MPO and 4 MPa) are displayed in Figure 5. As it can be observed, the drying path causes limited variations of the dry density. These variations are less than 2% for both raw tufa and tufa-lime mixtures. In addition, it can be noted that about 60% of these variations occur during the first day of drying. This behavior can be related to the nature of the material under study (Clayey-sand of low plasticity) and to the preparation mode (static compaction at maximum dry density). Thus, the effect of dry density on the variations of thermal conductivity is not considered in this study. For this reason, the results and discussions are mainly focused on the effects of water content and degree of saturation on the thermal conductivity.

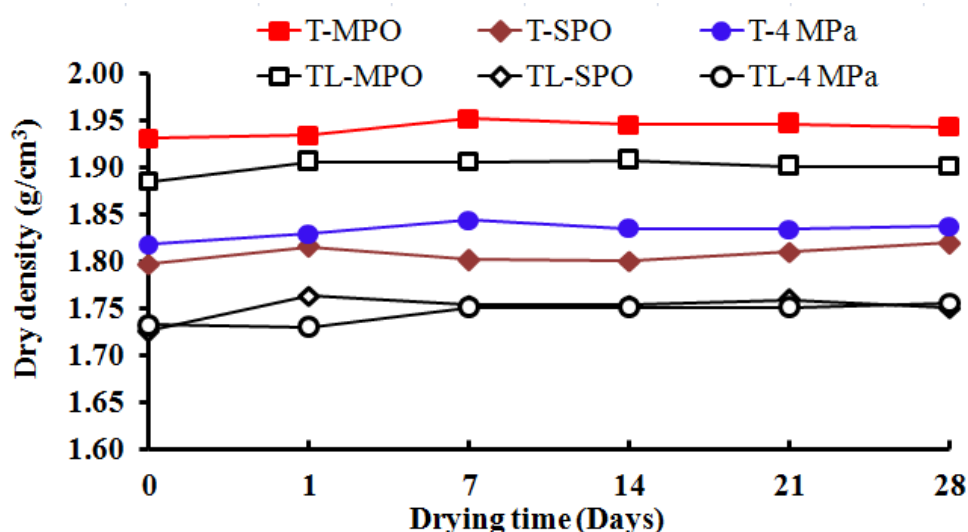


Figure 5. Variation of dry density as a function of drying periods

### 3.1. Effect of the Hydric State

The effect of water content ( $w$ ) on the thermal conductivity ( $\lambda$ ) for each mix was evaluated and is presented in Figure 6. In the initial state (undried samples), a general linear decreasing tendency of thermal conductivity with water content is observed. Table 5 presents the regression equations for the global relationships. After one day of drying, the thermal conductivity decreased by about 26% for all samples, which corresponds to a water content decline of 55%. Then, during the following 27 days of drying, the thermal conductivity dropped by 25%, while the water content declined by 35%.

It is worth noting that a constant slope ( $\Delta(\lambda)/\Delta(w)$ ), ranging between 4 and 5%, was observed in the linear tendency for all tests. This result helps to estimate the thermal conductivity in the dry state. The average thermal conductivity was found equal to  $0.72 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  for raw tufa samples and  $0.56 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  for the stabilized samples (Table 4).

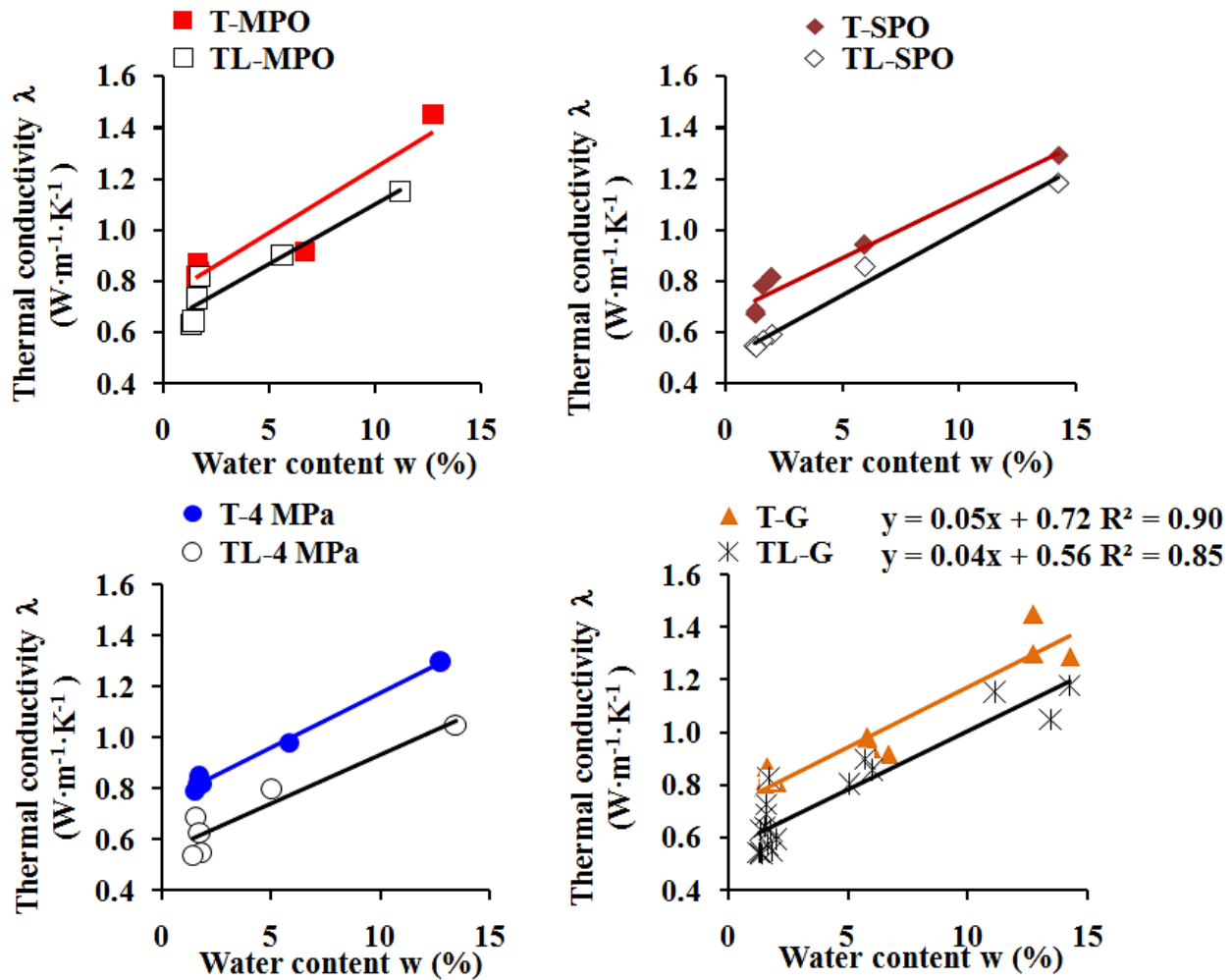


Figure 6. Variation of thermal conductivity ( $\lambda$ ) versus water content ( $w$ ), for different compaction energies (MPO, SPO, 4MPa)

Table 4. Equations and regression coefficients for different water contents

Materials	Global Relationships	Equations	R <sup>2</sup>
Tufa (T)	T-G	$\lambda=0.05 w + 0.72$	0.90
Tufa + 4% Lime (TL)	TL-G	$\lambda=0.04 w + 0.56$	0.85

Figure 7 illustrates the curves representing the variation of thermal conductivity ( $\lambda$ ) versus water content ( $w$ ), for raw studied material compared, with others found in the literature. The selected values were collected from studies covering materials with dry densities equivalent to those of our samples (from 1.7 to 1.9  $\text{g}/\text{cm}^3$ ). Except the result of Meukam et al. (2004) and Phung (2018) [12, 14], where the evolution of the thermal conductivity seems to be nonlinear (in particular for high water content values), the other results follow a linear tendency with different slopes (7-12%), which is in agreement with our results. As reported by Laurent (1987) [11], the slope of the evolution of the thermal conductivity depends on the nature of the material. In this case, it can be observed that the thermal conductivity measured in this study presents generally the lowest values compared with the other results.

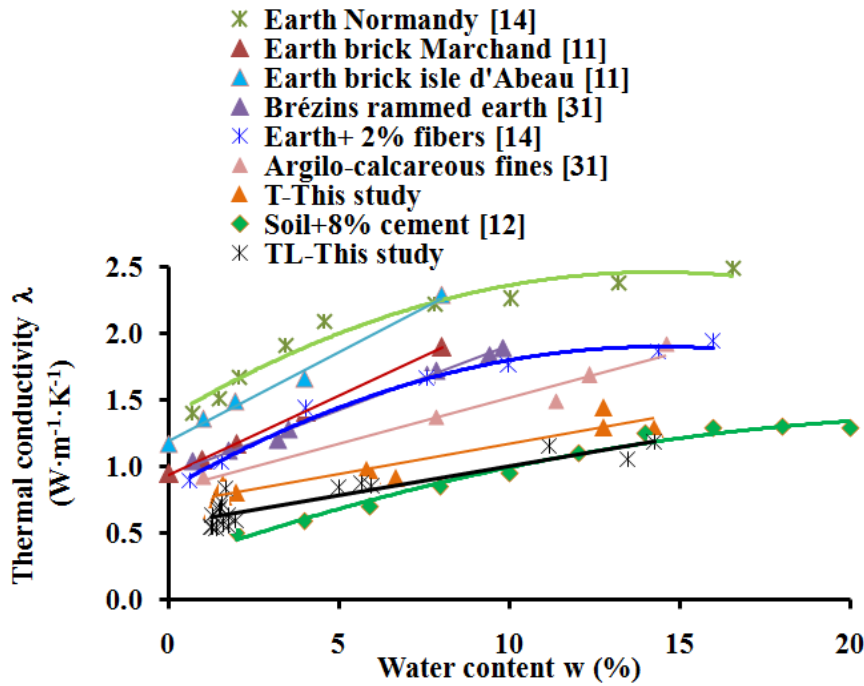


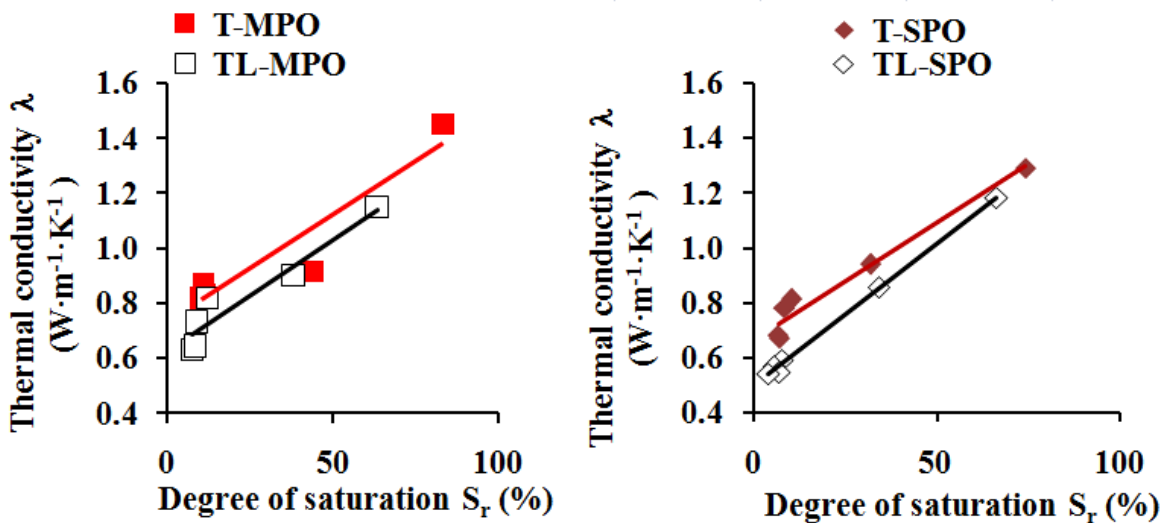
Figure 7. Thermal conductivity versus water content for different raw and stabilized earth materials

The effect of the degree of saturation ( $S_r$ ) on the thermal conductivity ( $\lambda$ ) for different samples is presented in Figure 8. Likewise, the effect of water content, a linear variation trend was also observed between the thermal conductivity and degree of saturation for both raw and stabilized samples (Table 5). From the beginning to the end of drying process, a general decrease, ranging between 41 to 53% and 39 to 48%, respectively was observed for the thermal conductivity of the raw and stabilized samples.

A constant slope ( $\Delta(\lambda)/\Delta(S_r)$ ) of 1% was observed for all tests. Also, the thermal conductivity in the dry state is close to their found in the ( $w, \lambda$ ) diagrams. The average thermal conductivity was found equal to  $0.71 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  for raw tufa samples and  $0.55 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  for the stabilized samples (Table 5).

Table 5. Equations and regression coefficients for different degrees of saturation

Materials	Global Relationships	Equations	R <sup>2</sup>
Tufa (T)	T-G	$\lambda = 0.01 S_r + 0.71$	0.93
Tufa + 4% Lime (TL)	TL-G	$\lambda = 0.01 S_r + 0.55$	0.90



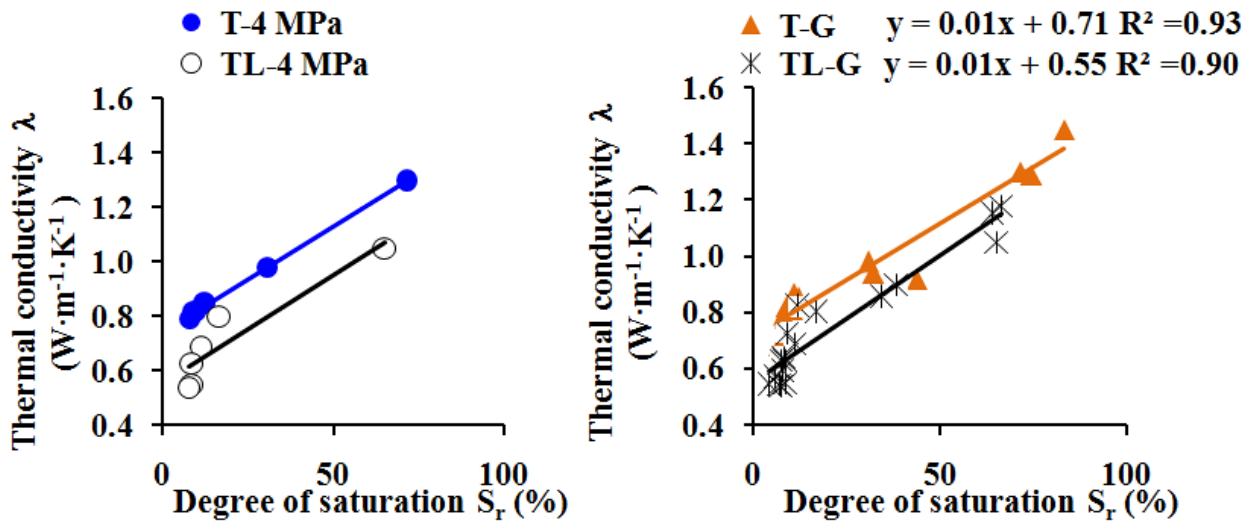


Figure 8. Variation of thermal conductivity ( $\lambda$ ) versus degree of saturation ( $S_r$ ), for different compaction energies (MPO, SPO, 4MPa)

More results, found in the literature, about thermal conductivity are plotted against the degree of saturation in Figure 9. It concerned results of Hall et al. (2009), Alrtimi et al. (2016) and Chen (2008) [32-34] obtained on different earth building material. The collected data shows that the thermal conductivity varies linearly, with the degree of saturation. This is in agreement with our results. The evolution of the thermal conductivity took place with different slopes depending on the nature of the material. As the degree of saturation represents the ration between the volume of the water phase and total volume, it can be concluded that the studied materials reflect the dependency of its thermal behavior as function of the distribution of water within the solid matrix.

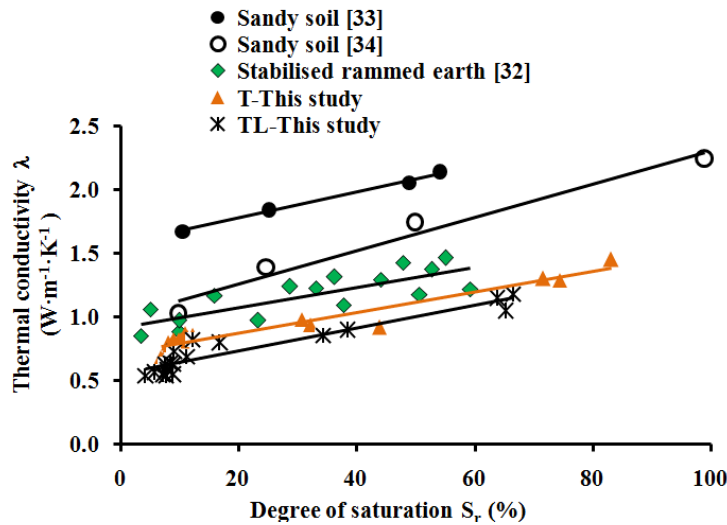


Figure 9. Thermal conductivity versus degree of saturation, for different earth materials

During the drying process, the degree of saturation (water contents) decreased, which is translated by a progressive replacement of the water contained in the pores by air bubbles that will then form a continuous air phase [35, 36]. It is commonly acknowledged that the thermal conductivity of air is about 20 times smaller than that of water [37]. Therefore, drying process of the material leads to a decrease in its thermal conductivity. As reported by [12], these processes took place in three stages: (i) When the soil is quasi-saturated, (high value of water content), high values of thermal conductivity can be registered. This state corresponds to a state of continuous path formation where the heat transfer is through thermal bridges constituted from water phase and contacts between soil grains (Figure 10.a). Similar tendencies were observed in other studies [12-14]. (ii) The decrease in water content leads to less formation of thermal bridges or heat conduction bridges within the material and as result, its thermal conductivity decreases (figure 10.b). (iii) For low water contents or degree of saturation, heat transfer takes place essentially at the points of contact between the grains forming the material, which can explain the small increasing steps in thermal conductivity (figure 10.c). Thus, it can be deduced that the behavior observed in this study concerns essentially the two last phases described below, since the degree of saturation in the most of studied cases is between 4 and 90% ( $w=1.5$  to 15%). However, this interval covers the water content range corresponding to those registered for earth buildings [11].



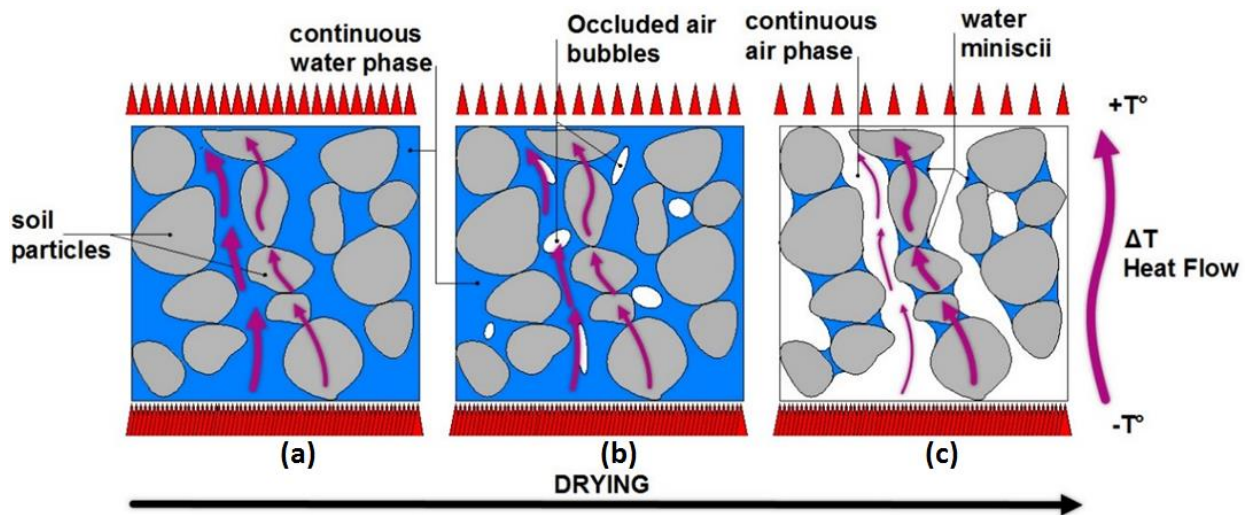


Figure 10. The effect of drying process on the thermal conductivity

### 3.2. Effect of Lime Treatment

Furthermore, the curves representing the variation of the thermal conductivity of stabilized tufa are below those of raw tufa (Figures 6 and 8). Therefore, it should be mentioned that lime treatment induces a decrease in thermal conductivity, between 9 and 30%, with respect to that of raw samples, at different energies. This finding is in accordance with Liuzzi et al. (2013) and Akinmusuru (1994) [17, 18]. This can be attributed to: (i) Porosity increase due to the agglomeration-flocculation phenomenon [38, 39]. As suggested by [40], the calcium cations ( $Ca^{2+}$ ) migrate from the hydrated lime to the clay minerals surface causing the displacement of water and other ions. Consequently, particles tend to agglomerate, and the soil becomes friable and granular thus leading to higher porosity, (ii) Lower thermal conductivity ( $\lambda=0.1012 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) of the pozzolanic lime products, such as calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H) resulting from the hydration process [41-43]. Since the thermal conductivity of soil is controlled by that of its constituents, the presence of the above hydrates (C-S-H and C-A-S-H), notably around the agglomerates [44], can have a significant impact on the thermal conductivity of the entire system.

### 3.3. Comparison of Thermal Conductivity with Conventional Materials

Figure 11 illustrates a comparison between the thermal conductivities obtained in our study and those of some conventional construction materials such as concrete, fired and unfired bricks and sand-lime brick [45]. For the sake of comparison, the thermal conductivity of concrete is approximately equal to  $2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , which indicates that the average thermal conductivity of our earth-based materials is approximately 4 times lower than that of concrete. We can also note that this value is lower by 1.15 to 1.4 times than that to adopted characteristic values of thermal conductivity of earth material and sand-lime brick.

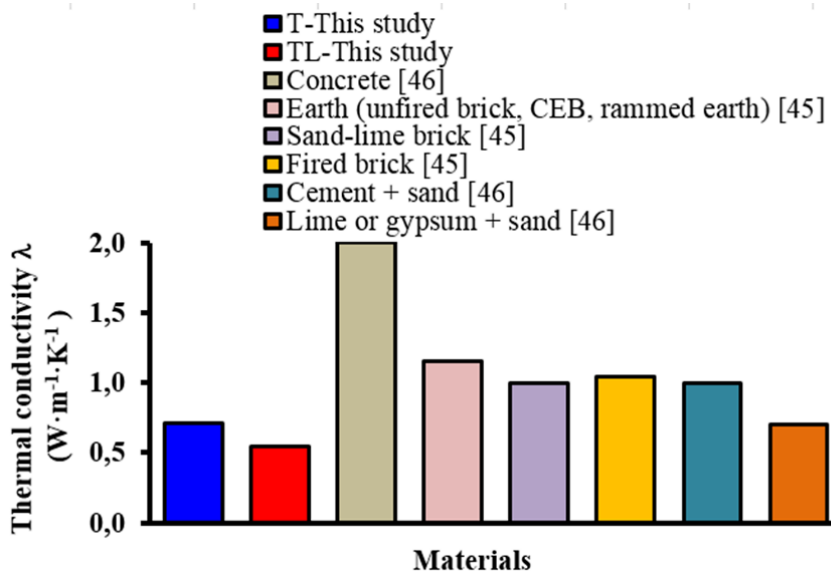


Figure 11. Comparison between the thermal conductivities obtained in our study and those of other materials

## 4. Conclusions

This article aims to assess the thermal conductivity of stabilized and raw compacted tufa used as an earth building material. Evaluating this material's property is strongly recommended in the construction industry owing to its effective role in terms of insulation and thermal comfort. Several conclusions were drawn:

- The drying process has great influence on the water content and degree of saturation of raw and stabilized tufa. Consequently, decreasing in the water content and degree of saturation causes a decrease in thermal conductivity. This means that thermal insulation is significantly improved.
- A linear correlation was found to be the best-fit to describe the relationship between the thermal conductivity and both water content and degree of saturation. These simple relations can be easily introduced into numerical algorithms and models that involve thermal behavior.
- The addition of lime has an impact on the thermal conductivity. Note that, for all compaction energies, the stabilized tufa samples exhibited lower thermal conductivity in comparison with raw tufa. The lowest measured thermal conductivity was approximately equal to  $0.49 \text{ (W.m}^{-1}\text{.K}^{-1}\text{)}$ . This value was recorded for the compacted stabilized samples (TL-SPO), after 28 days of drying.
- The above thermal conductivity value was found to be lower than that of some conventional construction materials such as: concrete, fired bricks and sand-lime bricks. This means that thermal comfort may appreciably be improved using this local material. Furthermore, energy consumption for heating and air conditioning can significantly be reduced.

Future studies will be focused on the hygric properties of the raw and stabilized in order to investigate the response of compressed earth brick walls with respect to hygrothermal loads.

## 5. Declarations

### 5.1. Author Contributions

K.M.; Methodology, Investigation, Data collection. F-E M.D.; Conceptualization, Visualization, Resources, Writing - review & editing, Supervision. A.L.; Data curation, Writing - review & editing. N.A.; Conceptualization, Formal analysis, Validation, Writing - review & editing, Supervision. All authors have read and agreed to the published version of the manuscript.

### 5.2. Data Availability Statement

The data generated and/or analysed during the current study are available on reasonable request from the corresponding author

### 5.3. Funding and Acknowledgements

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### 5.4. Conflicts of Interest

The authors declare no conflict of interest.

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